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Study on the Physical Properties of Compound Soils Mixed with Argillaceous Shale and Loess

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Abstract

This study conducted field experiments on the compounding of argillaceous shale and loess, measured the particle size distribution and soil moisture characteristic curves of the compound soils, and investigated the effects of argillaceous shale content on the physical properties of the compound soils. The following conclusions were drawn: The higher the content of argillaceous shale in the compound soil, the lower the content of silt and clay particles in the soil. The more argillaceous shale in the compound soil, the greater the soil porosity and air permeability, while the water-holding capacity decreases. As the content of argillaceous shale in the soil increases, the soil's water supply capacity gradually decreases. There are significant differences in the field water capacity (FC), wilting coefficient (WP), and available soil water content (TAW) of soils with different compounding ratios, and the available soil water content gradually decreases with the increase of argillaceous shale content in the soil. The results can provide scientific references for land improvement projects in mountainous areas with mixed soil and stone.

Keywords

Argillaceous Shale; Compound Soil; Particle Size Distribution; Soil Moisture Characteristic Curve.

1. Introduction

During the implementation of land improvement projects, the sites are often located in mountainous areas with mixed soil and stone[1-3]. The local soil layer is generally thin and contains a large amount of weathered argillaceous shale. The physical properties of the soil determine the movement laws of water[4], fertilizer, air, and heat in the soil, which are important factors affecting crop growth and key to determining the benefits of land improvement projects[5-7]. Therefore, it is of great scientific significance and practical demand to study the physical properties of compound soils mixed with argillaceous shale and loess.

2. Materials and Methods

2.1. Collection of Soil Samples and Compounding Ratios

The study area is a residual loess hilly area with an altitude of 1196–1384 m, and the slopes of the hills have exposed rocks with a gradient of 10°–25°. The soil bodies in the study area mainly include aeolian loess, alluvial loess, silty clay, and gravel. Through field surveys, soil samples of loess and argillaceous shale were collected from the study area, and the particle size distribution, soil nutrients, and heavy metal elements of the soil samples were analyzed. Loess and argillaceous shale were compounded at ratios of 95:5, 90:10, and 85:15. The compounded soils were mixed evenly by a rotary tiller and then sampled again after one year of settling. Ten replicates were collected from each plot and brought back to the laboratory to measure the particle size distribution and soil moisture characteristic curves. The results are shown in Tables 1 and 2.

Table 1. Particle size distribution of loess and argillaceous shale

Sample No.	pH Value	Electrical Conductivity (ds/m)	Particle Size Composition (%)			Texture (USDA)
Loess	8.1	0.133	17.71	79.94	2.35	Silt loam
Argillaceous Shale	8.1	0.137	13.99	83.03	2.98	Silt loam

Table 2. Soil nutrients of loess and argillaceous shale

Sample No.	Organic Matter (g/kg)	Available Phosphorus (mg/kg)	Available Potassium (mg/kg)	Total Nitrogen (g/kg)
Loess	4.5	0.8	62	1.35
Argillaceous Shale	26.5	0.9	73	2.18

2.2. Experimental Methods

Table 3. Heavy metal elements in loess and argillaceous shale (mg/kg)

Sample No.	Chromium	Nickel	Copper	Zinc	Arsenic	Cadmium	Lead
Loess	63.67	20.9	22.1	84	3.9	0.12	27.4
Argillaceous Shale	73.67	30	29.1	105.9	13	0.15	32.2

Table 4. Compounding settings of loess and argillaceous shale (%)

Case	Loess	Argillaceous Shale
A_1	95	5
A_2	90	10
A_3	85	15

The air-dried soil was ground and sieved (samples for total element analysis were 0.25 mm, and those for available nutrients were 1 mm) and then stored in paper bags for later use. The total nitrogen content of the soil was determined using a FOSS 8400 fully automatic Kjeldahl nitrogen analyzer. Soil samples were naturally air-dried, passed through a 2 mm sieve, roots were removed, and about 0.5 g of soil sample was taken. Thirty percent hydrogen peroxide (H_2O_2) was added and soaked for 24 hours to remove organic matter. After dilution with distilled water, the mixture was allowed to settle. The supernatant was removed to remove acid. After ultrasonic treatment for 30 seconds, the soil particle size volume fraction (%) was measured using a Mastersizer 2000 laser particle size analyzer. The particle sizes were set at 2–1 mm (d_1), 1–0.5 mm (d_2), 0.5–0.25 mm (d_3), 0.25–0.1 mm (d_4), 0.1–0.05 mm (d_5), 0.05–0.002 mm (d_6), and <0.002 mm (d_7), totaling 7 levels. According to the USDA classification standard, they were divided into very coarse sand (2–1 mm), coarse sand (1–0.25 mm), fine sand (0.25–0.05 mm), silt (0.05–0.002 mm), and clay (<0.002 mm). The results are shown in Tables 3 and 4.

Soil moisture characteristic curves were measured using a high-speed constant-temperature freezing centrifuge (Hitachi CR21G). At 20°C, 12 different speeds were set (corresponding to suction values of 0.01, 0.1, 0.2, 0.4, 0.6, 0.8, 1, 2, 4, 6, 8, and 10 bar). The soil mass water content of the test soil samples was recorded at 12 suction levels during the test. The contraction of the test soil samples under centrifugal force was also recorded, and the soil volume water content corresponding to different suction forces was calculated to obtain the soil moisture characteristic curve of the test soil samples. Finally, the average value of three soil samples in each layer was taken as the soil moisture characteristic curve of the rotary layer. The effective water content was derived from the soil moisture characteristic curve simulation equation. Generally, the soil water content at a soil suction of 0.3 bar is considered the field water capacity, and that at 1.5 bar is considered the wilting coefficient. The difference between the field water capacity and the wilting coefficient is the maximum available water content of the soil.

2.3. Data Analysis and Processing Methods

The RETC software was used to fit the soil moisture characteristic curve, and the Gardner model was chosen for the fitting. Assuming that soil pores are circular capillaries of various diameters, the relationship between soil water suction (S) and capillary diameter (d) can be expressed as:

$$S=4\delta/ d \tag{1}$$

In equation (1), S is the suction force in Pascals (Pa), δ is the surface tension coefficient of water, which is generally 7.5×10^{-2} N/m at room temperature, and d is the equivalent pore diameter in meters (m).

The soil moisture characteristic curve fitting model, the Gardner model, is given by:

$$\theta=ah^{b} \tag{2}$$

In equation (2), θ is the soil volume water content (cm^3/cm^3), h is the soil water suction in bars, and the parameters a and b determine the shape of the curve. Parameter a indicates the water-holding capacity, while parameter b indicates the rate at which soil water content decreases with decreasing soil water potential.

3. Results and Analysis

3.1. Statistical Characteristics of Silt and Clay Particles in Soil

The content of silt and clay particles in the soil determines soil quality and crop production. In this study, the content of silt and clay particles in the compound soils was statistically analyzed (Table 5). The results showed that as the content of argillaceous shale increased, the content of silt and clay particles in the soil gradually decreased. When the content of argillaceous shale was 15%, the content of silt and clay particles in the soil was the lowest. This is mainly because the particle composition of argillaceous shale is relatively coarse. The coefficient of variation (CV) of the three compound soils was 13.67%, 14%, and 12.90%, respectively. According to the classification system of Nielsen and Bouma (1985)[8], CV ≤ 10% indicates weak variation, 10% < CV < 100% indicates moderate variation, and CV ≥ 100% indicates strong variation. The CV of silt and clay particles in the three compound soils was all moderate variation. The K-S test was performed on the three compound soils, and the results showed that the P values of the three compound soils were all greater than 0.05, indicating that the content of silt and clay particles in the three compound soils followed a normal distribution.

Table 5. Statistical characteristics of silt and clay particle content in soils with different compounding ratios

Depth	Mean Value	Standard Deviation	Minimum Value	Maximum Value	K-S (P)	CV/%
A_1	82.98	11.34	50.48	99.86	1.22	13.67
A_2	80.70	11.30	41.40	98.11	1.10	14.00
A_3	79.15	10.21	52.88	97.55	1.06	12.90

3.2. Effects of Dam Site Stratified Accumulation on Soil Pores

The equivalent pore diameter of the soil can reflect the distribution of pore sizes in the soil. If the equivalent pore diameter corresponding to soil water content θ_1 is d_1, and that corresponding to soil water content θ_2 is d_2, then the ratio of the volume of pores with diameters between d_2 and d_1 to the total pore volume in the soil is $\theta_1 - \theta_2$ ($\theta_1 > \theta_2$)[9]. Therefore, based on the distribution of pore sizes in different treated soils, the changes in the water-holding capacity of different treated soils can be analyzed. The equivalent pore diameter of the soil was calculated using equation (1). In this experiment, the equivalent pore diameters corresponding to soil water suction were 0.3, 0.03, 0.015, 0.0075, 0.005, 0.00375, 0.003, 0.0015, 0.00075, 0.0005, 0.000375, and 0.0003 mm. The equivalent pore diameters were divided into low suction segment, medium suction segment, and high suction segment, corresponding to equivalent pore diameters of 0.03–0.3 mm, 0.00375–0.03 mm, and 0.0003–0.00375 mm, respectively. As shown in Table 6, in the high suction segment (0.03–0.3 mm), the proportion of total pores in compound soil A_1 was less than 10%, significantly lower than that in compound soils A_2 and A_3, indicating that compound soil A_1 had fewer large pores, while compound soils A_2 and A_3 had more large pores. In the medium and low suction layers (0.00375–0.03 mm and 0.0003–0.00375 mm), the proportion of total pores in compound soil A_1 was significantly higher than that in compound soils A_2 and A_3, indicating that the larger the equivalent pore diameter of the soil, the weaker the water-holding capacity of the soil, and vice versa. The more argillaceous shale in the compound soil, the greater the soil porosity and air permeability, while the water-holding capacity decreases.

Table 6. Distribution proportion of equivalent pore diameters at different depths

Equivalent Pore Diameter (mm)	A_1 (%)	A_2 (%)	A_3 (%)
0.03–0.3	2.12	10.76	14.61
0.00375–0.03	8.99	13.59	11.84
0.0003–0.00375	11.62	3.64	2.53

3.3. Effects of Dam Site Stratified Accumulation on Soil Water-Holding Capacity

Specific water capacity (C) is an important indicator for evaluating the soil's water supply capacity under different suction conditions[10]. The first-order derivative of the Gardner model (equation 2) gives the expression for specific water capacity of different soil layers, as shown in Table 7. Generally, the specific water capacity value at a soil suction of 1 bar can well represent the soil's water supply capacity[11]. When the soil suction was 1 bar, the specific water capacity of the three compound soils was $A_1 > A_2 > A_3$ (Table 7). As the content of argillaceous shale in the soil increased, the soil's water supply capacity gradually decreased. Generally, the soil water content at soil suctions of 0.3 bar and 15 bar corresponds to the field water capacity (FC) and wilting coefficient (WP) of the soil, respectively. The difference between the two is the available soil water content (TAW). The field water capacity (FC): $A_1 > A_2 > A_3$; wilting coefficient (WP): $A_1 > A_2 = A_3$; available soil water content (TAW): $A_1 > A_2 > A_3$. There were significant differences in the field water capacity (FC), wilting coefficient (WP), and available soil water content (TAW) of soils with different compounding ratios. As the content of argillaceous shale in the soil increased, the available soil water content gradually decreased.

Table 7 Specific water capacity expressions and water-holding capacity of different soil layers

4. Conclusion

Through field experiments on the compounding of argillaceous shale and loess, the particle size distribution and soil moisture characteristic curves were measured, and the effects of argillaceous shale content on the physical characteristics of the compound soils were analyzed. The following conclusions were drawn:

The higher the content of argillaceous shale in the compound soil, the lower the content of silt and clay particles in the soil. The coefficient of variation (CV) of the three compound soils was 13.67%, 14%, and 12.90%, respectively, all indicating moderate variation. The content of silt and clay particles in the three compound soils followed a normal distribution.

The more argillaceous shale in the compound soil, the greater the soil porosity and air permeability, while the water-holding capacity decreases. In the high suction segment (0.03–0.3 mm), the proportion of total pores in compound soil A_1 was less than 10%, significantly lower than that in compound soils A_2 and A_3. In the medium and low suction layers (0.00375–0.03 mm and 0.0003–0.00375 mm), the proportion of total pores in compound soil A_1 was significantly higher than that in compound soils A_2 and A_3.

As the content of argillaceous shale in the soil increased, the soil's water supply capacity gradually decreased. The specific water capacity of the three compound soils was $A_1 > A_2 > A_3$. There were significant differences in the field water capacity (FC), wilting coefficient (WP), and available soil water content (TAW) of soils with different compounding ratios. As the content of argillaceous shale in the soil increased, the available soil water content gradually decreased.

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